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Organic solid waste originating from the meat processing industry as an alternative energy source

Elaine Virmond [a,*], Robson L. Schacker [a], Waldir Albrecht [b], Chtistine A. Althoff [b], Maurício de Souza [a], Regina F.P.M. Moreira [a], Humberto J. José [a]

[a] *Laboratory of Energy and the Environment, Department of Chemical Engineering and Food Engineering, Federal University of Santa Catarina, Trindade, Florianópolis-SC 88040-900, Brazil*

[b] *Albrecht Industrial Equipments Ltd, BR-101, km 29, Pirabeiraba, Joinville-SC 89239-500, Brazil*

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ABSTRACT

The biosolids originating from the wastewater treatment process of two meat processing plants (LFP and LFG) were characterized as a fuel and their potential for utilization as alternative energy sources was assessed through the combustion of LFP in a pilot scale cyclone combustor. A comparative evaluation of the LFP, LFG and SD (sawdust) properties as well as the emissions during the combustion test was performed. The high energy content of LFP (LHV (lower heating value) equal to 25.77 MJ kg^{-1}) and LFG (LHV = 25.89 MJ kg^{-1}), both dry and ash free (daf), combined with the high volatile matter content (85.29 and 85.61 wt%, daf, respectively) improve the ignition and burning of the solids. Also, the fouling and slagging tendencies of the ashes were predicted based on the fuel ash composition and ash fusibility correlations. The emissions of CO, SO_2, and NO_x and total organic carbon (TOC) were compared to guideline limits established by Brazilian and international legislation. The TOC concentrations were below the emission limits. The high level of nitrogen in LFP (9.24 wt%, daf) led to high levels of NO_x. In this regard, further combustion tests are being performed by the authors.

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1. Introduction

Combustion technology has undergone substantial changes over the last decade or so, and the application of thermal conversion processes to biomass fuels has increased worldwide due to the energy exploitation potential of wastes as well as to the significant increase in environmental awareness in the industrial sector [1–3].

Cyclonic furnaces have been considered as an option in large-scale utility boilers and certain industrial processes where waste heat can be recovered profitably [4–6]. In cyclonic combustion the burning occurs at positive pressure, in a specially designed cylindrical reactor. Pulverized material is blown into the cyclone burner where it oxidizes immediately. Centrifugal action generates very high turbulence and forces the particles toward the cylindrical wall of the burner where char oxidation occurs, facilitating not only rapid combustion but also solid product removal.

Many solid industrial wastes can be classified as biomass, for example, the organic solid waste originating from the physico-chemical treatment of meat processing wastewater. The use of this biomass reduces the costs associated with its disposal (which has been prohibited in many locations by strict regulations) as it can directly and significantly reduce the mass and volume of such wastes, facilitate energy recovery and generally lower toxic gas emissions when compared to fossil fuels [7]. As long as emissions are below the specified legislative limits, changing energy policies lend support to the use of this type of biomass, and other locally-generated wastes, as a fuel source, as part of a move toward achieving low carbon economies.

The requirement to reduce carbon dioxide emissions has sparked interest in the use of many types of biomass, increasing both the demand for the characterization of alternative fuels and the proliferation of scientific papers concerned with this subject [8–11].

Brazil is currently implementing advanced programs aimed at the use of biomass energy, and several experimental and

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Abbreviations: A/F, Air-to-fuel ratio; $B/A_{(+P)}$, ash fusibility correlation 1; daf, dry and ash free; db, dry basis; DTG, derivative thermogravimetry; FC, fixed carbon; GC–MS, gas chromatography–mass spectrometry; LFG, meat industry wastewater sludge 1; LFP, meat industry wastewater sludge 2; LHV, lower heating value; O_{2ref}, reference oxygen content; $Rate_{Max}$, maximum mass loss rate; $R_{S(+P)}$, ash fusibility correlation 2; SD, sawdust; TGA, thermogravimetric analysis; TOC, total organic carbon; VM, volatile matter; VOC, volatile organic compounds.

* Corresponding author. Tel.: +55 48 3721 6441; fax: +55 48 3721 9687.
E-mail addresses: e_virmond@yahoo.com.br, elainevirmond@gmail.com (E. Virmond).

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commercial projects are currently being implemented in Brazil, such as that presented by [12], to provide important information in order to overcome the technical and commercial barriers which inhibit the extensive implementation of bioenergy.

Existing combustion systems require modifications in order to accommodate the nature of the thermal behavior of biomass materials. Greater understanding of the physical and chemical processes occurring in the biomass during heating will aid the design and optimization of practical conversion systems. Inadequate design or operation of such waste fuel combustion system can result in the emission of pollutants and toxic organic compounds, such as the monoaromatic hydrocarbons BTEX (benzene, toluene, ethyl-benzene and xylene), which pose a serious threat to human health.

The processing of meat industry solid wastes has been applied mostly to the production of animal feed, which includes the slaughter wastes and the wastewater treatment solids as main ingredients [13,14]. However, diseases such as BSE (Bovine Spongiform Encephalopathy) have led to restrictions over the use of these wastes for feed processing. According to De Sena et al. [15], to avoid discharge and subsequent environmental problems, the combustion of these wastes, especially the sludge from the wastewater treatment plants, might offer a favorable solution also for economic reasons. These authors investigated the physicochemical treatment of a meat industry wastewater plant which can provide around 20% of sludge, an organic solid residue, aiming to obtain a biomass suitable for utilization as a biofuel for steam generation. The biomass to energy conversion can provide energetic and economic profits by reducing disposal and process costs, also representing an attractive option by increasing the use of renewable fuels.

In order to obtain acceptable and reusable products, a better understanding is required regarding the series of thermal events which take place during biomass combustion, as this will allow better control of the process [16,17]. Relevant information can be obtained by TGA (thermogravimetric analysis) and DTG (derivative thermogravimetry) in a relatively simple and straightforward manner. Combustion reactivity assessment by thermogravimetric analysis techniques for biomass fuels has been reported in the literature [18–22].

The fuel properties often form the basis of the selection of the most appropriate technology for the combustion process. Depending on these properties, a biomass fuel may not be suitable for specific combustion options, partially for technical and sometimes for environmental reasons. The characteristics of the biomass are influenced by its origin and also by the entire processing system preceding any conversion step.

Burning biomass containing different mineral matter compositions may create various problems, which can affect the boiler operation or make the firing of biomass in conventional combustion systems unprofitable. Many authors [23–26] have presented ash fusibility correlations to evaluate the influence of biomass combustion on boiler furnace fouling and wall slagging. The occurrence of these hazards is dependent on the chemical and mineralogical composition of the ash as well as on the conditions in the furnace (temperature and velocity distribution, reducing or oxidizing atmosphere and others). On considering these correlations, $B/A_{(+P)}$ proposed by Pronobis [24] seems to be most compatible with the biomass composition since it considers the influence of several ash constituents.

$$B/A_{(+P)} = \left[\frac{(Fe_2O_3+CaO+MgO+Na_2O+K_2O+P_2O_5)}{(SiO_2+Al_2O_3+TiO_2)}\right] \quad (1)$$

The ratio of basic to acid oxides considers the influence of phosphorus as P_2O_5 using Eq. (1), and it has been reported that the higher the value of $B/A_{(+P)}$ the higher the fouling tendency of the ash in a solid. The strong fouling tendency of chlorine compounds, when these are present in the biomass composition, leads to a higher amount of this element in the convection surface deposits, which can cause corrosion. The influence of sulfur should also be considered, as proposed by Zygarlicke *apud* Pronobis [27] in Eq. (2), where S_d is the percentage of S in the dry fuel. If $R_{S(+P)} < 0.6$, the slagging tendency is low; $R_{S(+P)} = 0.6–2.0$, medium; $R_{S(+P)} = 2.0–2.6$, high; $R_{S(+P)} > 2.6$, extremely high.

$$R_{S(+P)} = \left(B/A_{(+P)}\right)\cdot S_d \quad (2)$$

In strictly quantitative terms, the values of the above-mentioned fusibility correlation apply only to coal ash, for which there are many examples in the literature. For the combustion of the various types of pure biomass, the literature is much sparser and further investigations are required in this research area.

Critically related to the biomass properties is the emission of pollutants generated during combustion. Pollutant formation mechanisms and many other parameters related to the combustion process must be monitored due to the formation of highly problematic compounds such as PCDD/PCDF (polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans), VOC (volatile organic compounds), NO_x, SO_2, etc. [28–32]which must be controlled in order to comply with the stringent limits set by recent legislation.

During combustion the fuel N is mainly converted to gaseous N_2 and NO_x (NO, NO_2). NO_x can be formed via three different reaction pathways: thermal NO_x, prompt NO_x and fuel NO_x formation from the oxidation of fuel N.

Due to the comparatively low furnace temperatures in solid biofuel combustion plants (around 800–1200 °C), thermal and prompt NO_x formations are of minor importance. NO_x formation from the oxidation of fuel N (during a series of elementary reaction steps) is the most important mechanism in biomass combustion units [11]. According to Obernberger *apud* Obernberger et al. [33], emission problems (exceeding of emission limits) related to solid biofuels can be expected at fuel N concentrations above 0.6 wt% (db) and at fuel S concentrations above 0.2 wt% (db).

Acid gases may also be emitted, such as HCl (hydrogen chloride) if chlorine compounds are present in the biofuel composition and others if lead or other heavy metals are present. CO and HCs, including VOCs, are products of incomplete combustion. The reactions between HCl and the products of incomplete combustion (organic compounds) may lead to the formation of highly toxic compounds with potential carcinogenic effect, like PCDD/PCDF, through different mechanisms [34]. Monoaromatic compounds like BTEX (benzene, toluene, ethyl-benzene, and o-, m-, and p-xylenes) have high toxicity and are potentially mutagenic or even carcinogenic.

This paper presents a case study on the utilization of an organic solid waste (sludge) originating from the physicochemical treatment of meat processing wastewater as a renewable energy source in a combustion process for steam generation. The purpose was to characterize two different samples of sludge (LFP, LFG) as well as to assess the potential for their utilization as energy sources through the characterization of the gaseous emissions when one of these samples (LFP) was submitted to a combustion test in a pilot scale cyclone combustor. The emission levels observed were compared to current legislation limits. Wood and wood-based materials are extensively used as fuel for thermal energy generation particularly in the Brazilian food industry, which requires large amounts of steam. A comparative evaluation of the properties of LFP, LFG and SD, the burning profiles and the gaseous emissions obtained in the combustion tests performed in this study allowed the authors to identify the potential of these wastes as an alternative energy source for this industrial sector. Also, the prediction of the sinter and slag formation tendency of the ash was carried out based on analysis of the fuel ash composition, ash fusibility behavior and fusibility correlations.

2. Experimental

2.1. Biomass properties

The processes involved in the thermal utilization of solid wastes (fuel supply, combustion system, solid and gaseous emissions) are influenced by the kind of solid waste used, its physical characteristics and its chemical composition. The compositional elements of a waste are present in varying concentrations depending on its origin. Two different samples of organic solid wastes obtained from the physicochemical treatment of meat processing wastewater (LFP and LFG) were chemically and physically characterized, and their compositions were compared to that of SD (sawdust), taken as reference fuel. The biomass samples were first dried in an industrial rotating granulator drier with an operational capacity of 400 kg h^{-1} (model Bruthus, Albrecht, Brazil).

The biomass sample of LFP was sent to IVD, Laboratory for Analysis of Solid Fuels, Ash and Deposits, University of Stuttgart, Germany, for characterization. The other two samples were analyzed in different laboratories in Brazil. The repeatability of the runs was tested.

Ultimate analysis was carried out according to the ASTM D3176 method [35]. Oxygen content was calculated by difference. Proximate analysis was carried out following DIN 51718–20 methods [36–38] and heating values applying the methods ASTM D5865 [39] and DIN 51900 parts 1 and 3 [40,41]. Chloride and fluoride were measured using selective ion electrodes (Cole–Parmer), and phosphorus using colorimetric methods. The ash samples produced in the laboratory at 550 °C were characterized following the DIN51729-10 method [42].

The ash melting behavior of LFP was determined according to the IVD method, which is based on the tests described in ISO 540 [43] and ASTM D1857 [44]. The fuel ash was prepared in the laboratory following the standard procedure DIN 51719 [37]. However, for fuels with a high alkali content, as in the case of the biomass studied, the ash preparation was carried out at 550 °C or 600 °C (ashing of coals is carried out at 815 °C). The samples were prepared as pyramids, heated in CO_2 atmosphere with a heating rate of 10 K min^{-1} from 700 °C up to 1500 °C in a Carbolite Ash Fusion Furnace (CAF Video, Carbolite, United Kingdom). Through a control window at one end of the furnace tube the shape of the samples in the tube was video-recorded and the actual temperature during heating was registered. In contrast to the standard methods, the sample shrinkage was measured instead of identifying the defined temperature points. The temperatures of initial deformation, softening, hemispherical and fluid temperatures were determined by measuring the heights of the samples at intervals of 20 °C.

Thermogravimetric experiments were performed in order to predict the thermal behavior of the studied biomasses during the combustion process using a TGA-50 instrument (Shimadzu) with a heating rate of 10 °C min^{-1} up to 600 °C (SD) or 650 °C (LFP and LFG). The mass loss rate was determined in both synthetic air and helium atmospheres, at a flow rate of 0.5 L min^{-1}.

The ignition behavior was determined by comparing mass–temperature curves under inert and oxidizing conditions. The ignition temperature was taken as the temperature at which the mass loss curves in the oxidation and pyrolysis experiments deviate. As shown in the study by Grotkjær et al. [45], a number of parameters are known to influence the ignition temperature and ignition mechanism, these include sample mass, particle size (and possibly even geometry), volatile matter yield and oxygen concentration. In addition to these variables a number of system parameters related to the experimental conditions are important in terms of the ignition behavior.

2.2. Combustion tests

Combustion tests were carried out in a pilot scale horizontal cyclone type combustor (model Drako, Albrecht, Brazil), with a burning capacity of 100 kg h^{-1}. A scheme of the pilot plant is presented in Fig. 1.

The experimental equipment comprises: the main body of the horizontal cyclone combustor; fuel feeding system; oil burner for the start up of the system; air supply system (four fans: the first installed in the feeding system, the second in the oil burner, the third in the main body of the combustor for secondary air supply, and the fourth in the recirculation duct); temperature control system (two thermocouples inside the cyclonic combustion chamber, one at the inlet (point 1a in Fig. 1) and one at the outlet (point 1b in Fig. 1), and another one inside the cyclone ash separator, which is indicated by point 1c in Fig. 1. The chamber of the cyclone combustor is made of steel, with an internal layer of refractory bricks and the thermal insulation is provided by a refractory fiber-ceramic wool blanket. The combustion chamber dimensions are 1.5 m length and 0.4 m diameter, and it operates with a co-current flow of air and fuel.

LFP and SD biomasses were submitted to combustion tests to analyze their combustion behavior, combustion efficiency and gaseous emissions. The sampling point was located in the flue gas duct following US EPA Method 1 [46] recommendations, immediately after a cyclone used to separate the particulate matter. Oil was fired initially until the furnace temperature rose to around 800 °C so that biomass would be ignited. Operational conditions were adjusted to provide a stable burning in each test and the gaseous emissions composition was monitored, especially in terms of O_2, CO_2 and CO.

The combustion of SD was carried out at a fuel feed of 32 kg h^{-1} (moisture content of 9.16 wt%), with gas recirculation of 20% at an average temperature of 642 °C. The average temperature at the front stage of the combustor was 1052 °C and at the outlet of the combustor was 1024 °C, and an air-to-fuel ratio (A/F) of 9.08 (theoretical A/F of 7.23 based on the fuel composition) was used.

For the LFP combustion test, the conditions were: fuel feed of 43 kg h^{-1} (moisture content of 11.44 wt%), with gas recirculation of 20% at an average temperature of 800 °C. The average temperature at the front stage of the combustor was 868 °C and at the outlet of the combustor was 1080 °C, and an A/F of 11.82 (theoretical A/F of 7.76 based on the fuel composition) was used.

2.3. Emissions analysis

Flue gas samples were analyzed with a Greenline MK2 gas analyzer (Eurotron Italiana S.r.l.) for CO, O_2, SO_2, C_xH_y (measured as CH_4), NO and NO_2. NO concentrations were expressed as NO_2 for comparison with emission limits. CO_2 concentrations were calculated based on the fuel composition and on the excess oxygen.

2.3.1. BTEX analysis

The monoaromatic hydrocarbons BTEX (benzene, toluene, ethyl-benzene and xylene) were sampled by drawing flue gas through active charcoal tubes (CarbotrapTM 20–40 mesh, Sigma–Aldrich Co., United States) following the US EPA method TO-17

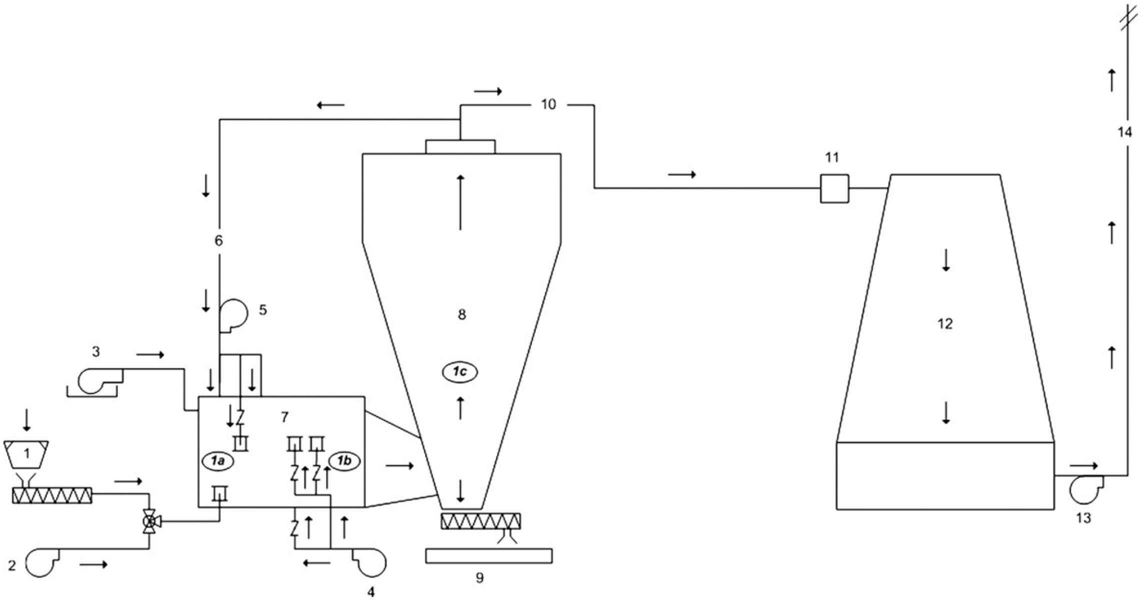

Fig. 1. Pilot scale cyclone combustor scheme. 1: Feed; 2: Primary air fan; 3: Oil burner; 4: Secondary air fan; 5: Flue gas recirculation fan; 6: Flue gas recirculation duct; 7: Cyclonic combustion chamber; 8: Cyclone ash separator; 9: Ash removal apparatus; 10: Exhaust gas; 11: Emissions sampling point; 12: Flue gas cooler; 13: Exhaustor; 14: Chimney; 1a, 1b and 1c: Points of temperature measurement.

[47], with modifications. BTEX analysis was carried out using an automatic TD (thermal desorption) system (model TD-20, Shimadzu, Japan) coupled with a GC–MS (model QP2010, Shimadzu, Japan). A Rtx®-5MS (5% diphenyl–95% dimethyl polysiloxane, Restek, United States) capillary column, with 30 m length, 0.25 mm ID and 0.25 μm film thickness, was used.

The desorption temperature applied was 300 °C, held for 30 min. Helium was used as the carrier gas, with a desorption flow rate of 60 mL min^{-1}. The GC operated from 50 °C (with a 5 min hold) heating at a rate of 5 °C min^{-1} to 180 °C and kept isothermal for 1 min at this temperature, with a split of 1/20. GC–MS analysis was performed in full scan mode, scanning from 48 to 600 (m/z). BTEX were identified and quantified using pure standards (BTEX mixture, 2.0 mg mL^{-1} in CH_3OH) and their concentrations were reported as TOC according to Technical Guidance Note M16 of the US EPA [48] for comparison with the specified legislation limits.

3. Results and discussion

3.1. Biomass properties

3.1.1. Composition of sawdust and meat processing sludges

Table 1 shows the properties of the biomasses characterized. Carbon (C), hydrogen (H) and oxygen (O) are the main components of the solid biofuels. The C and H contribute positively to the HHV (higher heating value). The content of H also influences the LHV (lower heating value) due to the formation of water. LFP and LFG have similar compositions given their origin, however, some differences were noted. The higher contents of C and H and lower ash content found in the LFG composition explain its higher LHV, which is 2.6% higher than that of LFP. Compared to SD, the LHV of LFP and LFG were 36.55% and 40.12% higher, respectively, due to their higher C and H concentrations, making this organic waste attractive for energy exploitation.

3.1.2. TGA/DTG trends

The information obtained from the TGA/DTG analysis is important for the setting of combustion parameters, allows a better understanding of the initial and final biomass degradation temperatures and can be used to investigate the reactivity of carbon materials. The results of the analysis are given as a plot of mass loss variation with temperature.

When heated in oxidizing atmospheres, solid biomasses lose moisture and volatile compounds, and both homogeneous combustion of VM (volatile matter) and heterogeneous combustion of FC (fixed carbon) take place. Also, mineral matter is oxidized forming ash.

The volatile matter content determines the flame stability during combustion. The high VM values observed for LFP and LFG (85.29 and 85.61 wt%, daf, respectively) lead to early ignition, at

Table 1
Biomass properties.

	Units	SD	LFP	LFG
Proximate analysis[a]				
Ash	[wt%, db[b]]	0.43	12.30	10.43
Moisture	[wt% raw]	19.97	15.00	21.00
VM[c]	[wt%, daf[d]]	79.78	85.29	85.61
FC[e]	[wt%, daf]	20.22	9.58	14.39
Ultimate analysis[a]				
C	[wt%, daf]	55.30	58.04	63.66
H	[wt%, daf]	7.14	9.01	9.48
N	[wt%, daf]	0.21	9.24	5.86
S	[wt%, daf]	<0.01	0.34	<0.01
O	[wt%, daf]	37.34	22.68	20.36
Cl	[wt%, daf]	<0.01	0.18	0.30
F	[wt%, daf]	<0.20	<0.20	<0.20
P	[wt%, daf]	0.01	1.03	0.64
Lower Heating Value[a]				
LHV[f]	[MJ kg^{-1}, daf]	16.62	25.77	25.89
LHV[f]	[MJ kg^{-1}, raw]	16.55	22.60	23.19

[a] Maximum experimental uncertainties equal to 0.30%.
[b] Dry basis.
[c] Volatile matter.
[d] Dry and ash free.
[e] Fixed carbon.
[f] Lower heating value.

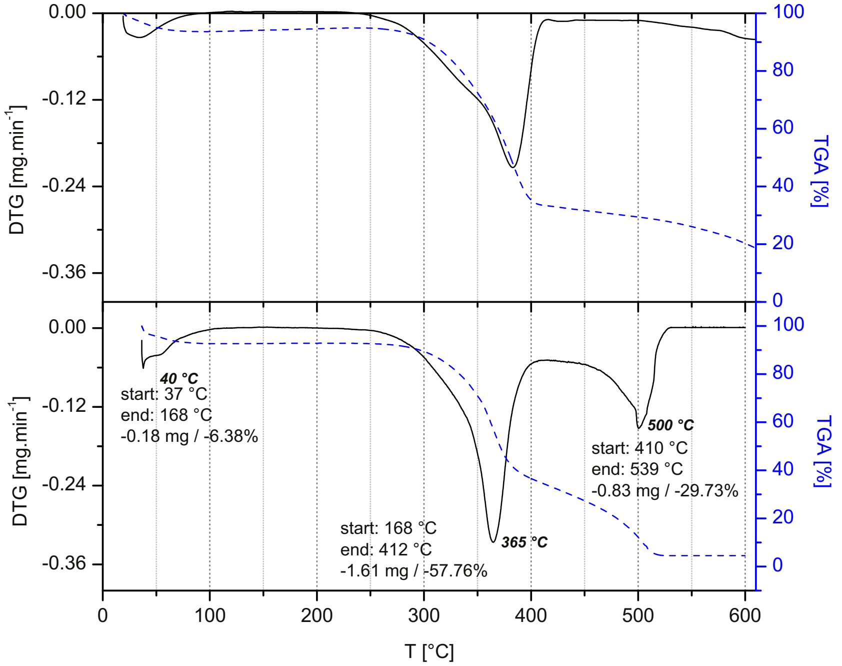

Fig. 2. TGA/DTG analyses of SD in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

lower temperatures (170–210 °C), achieving higher maximum mass loss rates, Rate$_{Max}$, (0.95 and 0.57 mg min^{-1} respectively, according to Figs. 3 and 4) compared to the ignition temperature of SD (around 300 °C) and its respective Rate$_{Max}$ (0.32 mg min^{-1}) in Fig. 2.

The burning stages may be either simultaneous or successive depending on the operational conditions, and are affected by heating rate, pressure, temperature and particle size. On the DTG curves for SD three distinct peaks are observed, whereas for LFP and LFG, there are four peaks, due to the intrinsic characteristics of each material. The first phase, usually at temperatures below 100 °C, refers to the water release in the case of biomass. The second phase, between 250 °C and 430 °C in Fig. 2 for SD (approximately 66% of total mass loss), can be attributed mainly to the thermal degradation of lignocellulosic materials that constitute sawdust and to the release of volatile matter, which mixes easily with oxygen and burns more easily than the fixed carbon. This is a fast burning region and the mass loss rate reaches its highest value, which gives

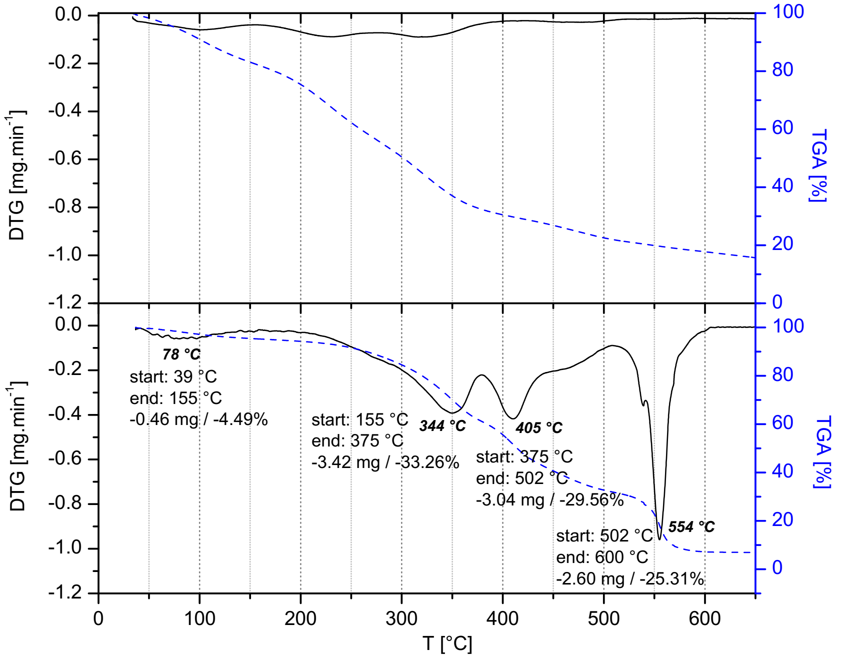

Fig. 3. TGA/DTG analyses of LFP in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

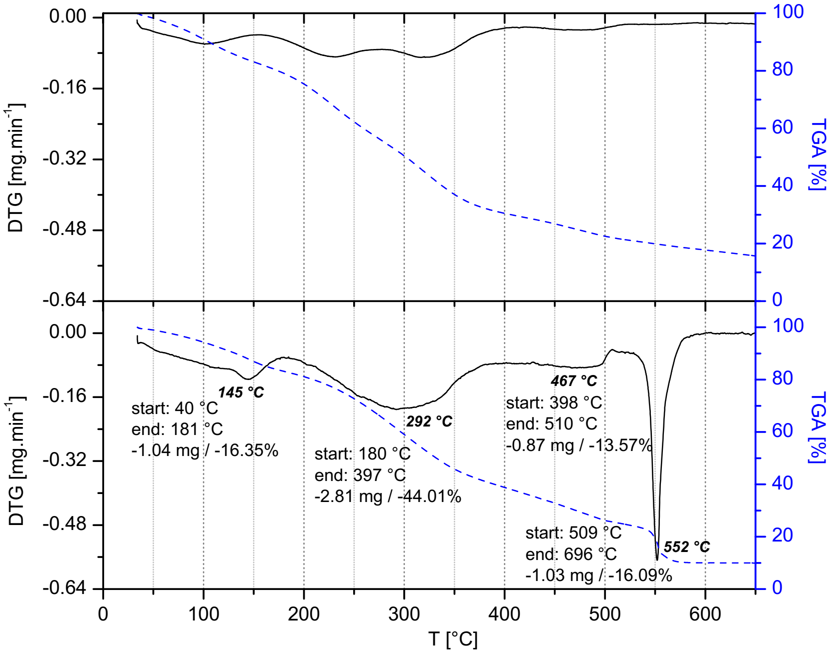

Fig. 4. TGA/DTG analyses of LFG in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

the peak temperature. The degradation of the fixed carbon for SD (approximately 20.22%, daf) generally occurs at approximately 450 °C–540 °C.

In the burning profile of LFP (Fig. 3) the mass loss observed from around 250 °C–600 °C can be attributed to the decomposition of different organic compounds, associated with the grease content (34.39 wt%, db) and to the volatile matter release, with a total contribution of around 84.4% of the total mass loss (comparable to the VM value obtained through the proximate analysis, 85.29 wt%). However, the behavior during the thermal degradation of LFP differs greatly from that observed for SD (Fig. 2), with the fast burning region occurring at higher temperatures. Approximately 23.68% of the biomass total mass was lost between 520 °C and 600 °C, probably representing the degradation of FC together with other constituents, mainly VM. It seems that VM is released gradually during the process until higher temperatures, while in SD the volatile matter combustion apparently prevails as a dominant single step of the combustion process, since the highest mass losses are concentrated in the intermediate temperature ranges (250–430 °C).

3.1.3. *Ash composition and ash fusibility trends*

The origin of the biomass influences the fouling and slagging properties. The dominant features of wood ash are its very high calcium content and the absence of sulfur. The lowest value for the ratio of basic to acid oxides, $B/A_{(+P)}$, and the zero value for $R_{S(+P)}$ indicate that the melting temperature of ash of this kind will be high, as reported by Llorente and García [25] and presented in Table 2, and even on radiation surfaces the deposits will be loose [24]. In comparison with SD, which is rich in acid oxides (SiO_2, Al_2O_3, TiO_2), LFP has higher contents of iron, phosphorus and calcium. Reports in the literature propose that the combination of alkalis and sulfur in LFP can promote slagging and fouling, as predicted through the ash fusibility correlations in Table 2 and confirmed by the low fusibility temperatures determined for LFP ash, which becomes fluid at 1040 °C, that is, 360 °C lower than in the case of SD.

As the calculated $R_{S(+P)}$ value (4.13) is higher than 2.6 (the reference value for this index), and $B/A_{(+P)}$ (13.76) is much higher than the value found for SD and for coal (0.28), as reported by Bryant et al. [49], the tendency toward fouling and slagging is extremely high. In the combustion system studied, even considering the short residence time of the LFP biomass inside the combustion chamber due to the high velocity promoted by the cyclone, the occurrence of these problems was observed.

The coagulant agent applied to the physicochemical treatment of the meat processing wastewater is of primary importance in

Table 2
Ash properties.

	Units	SD	LFP	LFG
Ash composition[a]				
Fe_2O_3	[wt%, db[b]]	4.44	32.40	2.28
CaO	[wt%, db]	31.27	17.40	43.05
MgO	[wt%, db]	11.64	1.30	3.51
Na_2O	[wt%, db]	1.67	1.70	1.80
K_2O	[wt%, db]	10.44	1.70	1.67
SiO_2	[wt%, db]	15.69	4.90	18.73
Al_2O_3	[wt%, db]	12.30	1.70	2.32
TiO_2	[wt%, db]	3.94	0.00	0.13
P_2O_5	[wt%, db]	2.74	36.30	23.28
MnO	[wt%, db]	2.06	n.d.[c]	0.10
SO_4	[wt%, db]	3.02	n.d.	3.14
Ash fusibility correlations				
$B/A_{(+P)}$		1.95	13.76	3.57
$R_{S(+P)}$		0.00	4.13	0.00
Ash fusibility temperatures				
Deformation temperature	[°C]	>1150[d]	750	n.d.
Softening temperature	[°C]	>1170[d]	990	n.d.
Hemispherical temperature	[°C]	>1190[d]	1010	n.d.
Fluid temperature	[°C]	>1230[d]	1040	n.d.

[a] Maximum experimental uncertainties equal to 0.30%.
[b] Dry basis.
[c] Not determined.
[d] Data from Llorente and García [25], for Eucalyptus I sample.

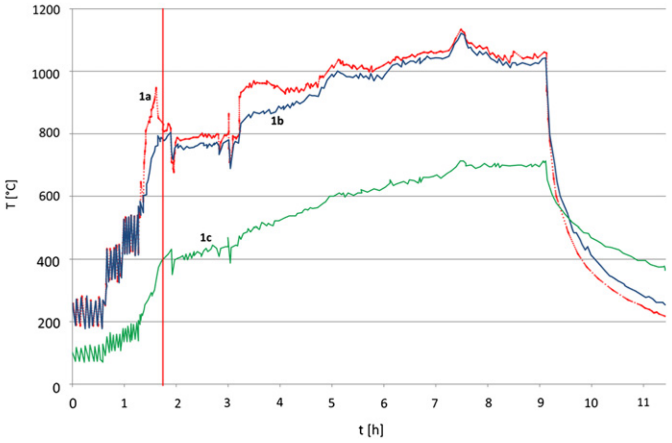

Fig. 5. Temperature profile for SD combustion test. Lines 1a and 1b: temperatures at the combustor inlet and outlet, respectively; Line 1c: temperature in the cyclone immediately after the combustion chamber.

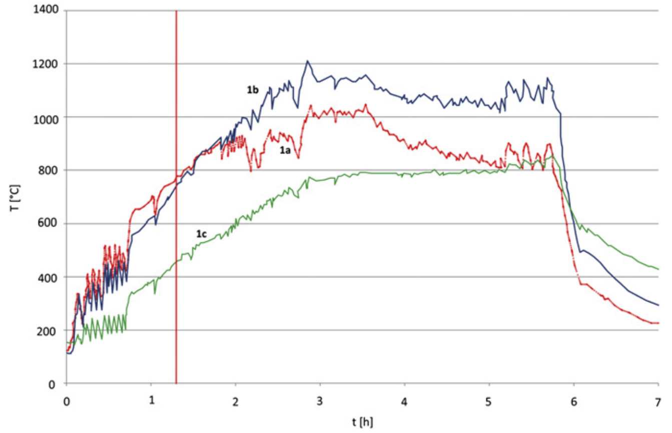

Fig. 6. Temperature profile for LFP combustion test. Lines 1a and 1b: temperatures at the combustor inlet and outlet, respectively; Line 1c: temperature in the cyclone immediately after the combustion chamber.

terms of the biomass and ash compositions. The utilization of ferric sulfate ($Fe_2(SO_4)_3$) in the physicochemical wastewater treatment that originates LFP modifies the base-to-acid $B/A_{(+P)}$ ratio due to an increase in the Fe_2O_3 concentration in the ash, favoring agglomeration. Substitution of this coagulant for aluminum sulfate $Al_2(SO_4)_3$, for example, would reduce the value of the $B/A_{(+P)}$ index of LFP in particular, and therefore minimize the agglomeration problem when pure LFP is burned. On comparing the ash compositions of LFP and LFG, it appears that a coagulant other than $Fe_2(SO_4)_3$ was applied in the wastewater treatment, resulting in a lower value for the $B/A_{(+P)}$ fusibility index (3.57). Alternatively, blending SD with LFP may produce minerals with much higher melting temperatures and the fouling tendency would decrease compared to the use of pure LFP.

Taking into account the higher ash content of LFP compared to SD, the influence of its co-combustion can be noted from the relatively low thermal fraction in the fuel. Virmond et al. [50] conducted a study on the co-combustion of SD and LFP in a mixing ratio of 9:1 (by weight) in the same pilot scale cyclone combustor considered in the present study. The characterization and evaluation of the mixture composition suggested that co-combustion represents a feasible option to reduce the occurrence of these problems. However, it requires further investigation to determine the influence of different proportions of LFP for use in the co-combustion process.

3.2. Combustion tests and emission analysis

3.2.1. Pilot scale horizontal cyclonic combustor

Figs. 5 and 6 show the profiles of the temperature inside the combustion chamber of the pilot plant during the tests performed with SD and LFP, respectively. Line 1a corresponds to the temperature in the front stage of the cyclonic combustion chamber and line 1b in the outlet. Line 1c relates to the temperature inside the cyclone ash separator immediately after the combustion chamber. The test time observed up to the vertical line highlighted in these figures indicates the period when the pilot oil burner was operating for the equipment start up.

The SM combustion test lasted for approximately 11 h while the LFP combustion test lasted for 7 h, both at temperatures ranging between approximately 750 and 1200 °C. The combustion behavior observed through the thermogravimetric analysis was reproduced as shown in the temperature profiles obtained during the tests on the cyclone type combustor. LFP ignites at the lowest temperature, achieves the highest combustion temperatures and burns rapidly in the outer part of the cyclone type combustor, resulting in a higher temperature at the combustor outlet (line 1b in Fig. 6) compared to the inlet, as it still releases VM at higher temperatures, as noted in Fig. 3, where the peak mass loss rate occurs (500–600 °C). Comparatively, the combustion temperatures during the SD burning increase gradually up to a maximum of around 1050 °C, reaching a higher temperature at the combustor inlet.

3.2.2. Emissions

Since no data on the combustion of meat processing or slaughterhouse wastes have been published to date, no comparison

Table 3
Gaseous emissions in the combustion tests.

	CO [mg Nm^{-3}]	CO_2 [%]	C_xH_y [mg Nm^{-3}]	NO_x[a] [mg Nm^{-3}]	SO_2 [mg.Nm^{-3}]	TOC [mg.Nm^{-3}]
SD biomass	93.58 ± 21.97	10.32 ± 0.03	0.00 ± 0.00	241.58 ± 26.31	0.00 ± 0.00	1.27 ± 0.57
LFP biomass	63.33 ± 10.30	10.33 ± 0.05	0.00 ± 0.00	1727.43 ± 229.93	363.54 ± 90.80	1.23 ± 0.12
CONAMA[b]	124.88	n.a.[c]	n.a.	560.00	280.00	n.a.
US EPA[d]	196.16	n.a.	n.a.	796.02	57.09	n.a.
17.BlmSchV (24 h; <50 MW)[e]	140.00	n.a.	n.a.	373.33	186.67	9.33
17.BlmSchV (24 h)[f]	70.00	n.a.	n.a.	280.00	70.00	14.00

[a] NO_x expressed in terms of NO_2.
[b] CONAMA 316/02, thermal treatment of wastes [51].
[c] Not applicable.
[d] US EPA, solid waste incineration [52].
[e] 17.BlmSchV 24 h; <50 MW, co-combustion of wastes [53].
[f] 17.BlmSchV 24 h, direct combustion of wastes [53].

was possible. However, the results for the contaminants reported in this paper were compared with the emission limits established by national and international environmental agencies, such as the Brazilian guidelines issued by The National Council of the Environment (CONAMA, [51]), for gaseous emissions in the thermal treatment of wastes; the American guidelines issued by the U.S. Environmental Protection Agency (US EPA, [52]), for emissions from commercial and industrial solid waste incineration units; and the German Guidelines 17.BlmSchV [53], for emissions from waste combustion and co-combustion. The gaseous emissions observed in the combustion tests and the respective regulation limits are reported in Table 3.

The average levels of gaseous emissions monitored during the combustion tests and the respective regulation limits were corrected to the reference oxygen content (O_{2ref}) of 7%.

C_xH_y was not detected and CO emissions for the fuels studied were below the limits established in the Brazilian, American and German regulations considered, except in the case of SD in relation to the German 17.BlmSchV 24 h guidelines, which refer to waste incineration and are stricter than the others. These are indications of complete combustion.

The effect of the biomass composition on the emissions resulting from their combustion was clearly observed, especially considering the N and S contents of LFP. Emissions of SO_2 are usually not significant for wood combustion due to the typically low concentrations of S in this fuel. As LFP had an S concentration of 0.34 wt% (db), above the reference value of 0.2 wt% (db), the emission of SO_2 is significant, as can be seen in Table 3.

NO_x emission (expressed as NO_2) in the SD combustion test was below all the regulation limits. However, in the LFP combustion, NO_x emissions were approximately 615% higher than the SD value, highlighting the influence of the higher fuel N content on the NO_x emission.

Besides the advantages in relation to the ash behavior, the co-combustion of SD and LFP would result in lower fuel N content and consequently in lower NO_x in the gaseous emissions than using LFP alone, as reported previously by the authors [50] when burning a 9:1 (by weight) mixture. An average NO_x concentration 247% lower than the value found for the combustion of pure LFP presented in this paper was observed, and the result was also under the limits established by CONAMA and US EPA. However, the energy recovery in this case would be lower given the lower calorific value of this mixture (LHV = 17.15 MJ kg^{-1}, daf, value obtained through mass balance considering homogeneous mixture) compared to pure LFP.

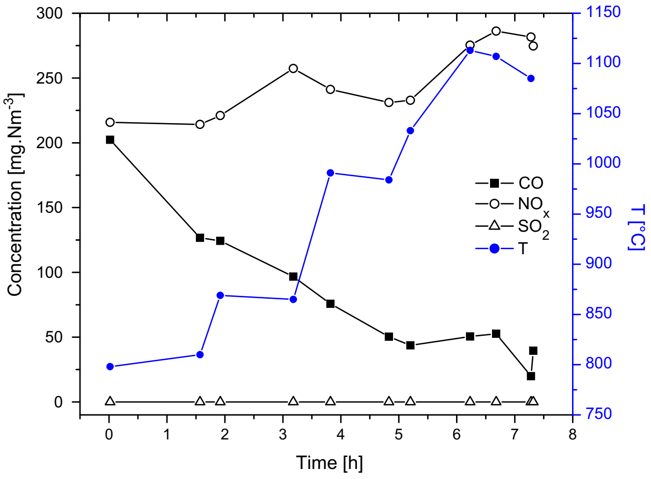

Fig. 7. CO, SO_2 and NO_x emissions for SD combustion test, O_{2ref} = 7%.

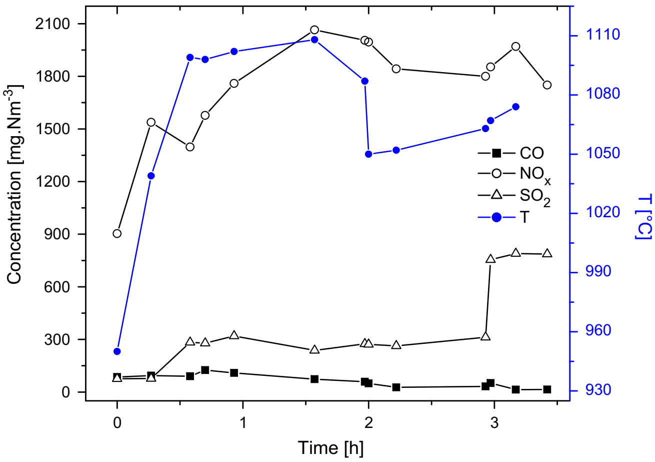

Fig. 8. CO, SO_2 and NO_x emissions for LFP combustion test, O_{2ref} = 7%.

In fact, this option is the most feasible in Brazil considering the high NO_x emissions related to both the fuel nitrogen and to the cyclone unit characteristics, and the fact that wood and wood-based materials are extensively used as fuel for thermal energy generation in the Brazilian food industry. Industrial solid wastes must be disposed of safely, and co-firing them with SD has been shown to be profitable in other studies by the authors currently underway using the same combustion plant and a different mixing ratio of SD and LFP (3:1 by weight). The advantages are both a reduction in the consumption of primary fuels and the recovering of energy from wastes which would normally be disposed of in landfills and potentially cause environmental problems.

As stated previously, the combustion temperature also influences the formation of NO_x, as seen in Figs. 7 and 8. As the N content in the SD was low, the NO_x concentration with SD combustion was influenced by the temperature in the combustion system.

Measures such as exhaust gas recirculation, air staging and staged addition of fuel could aid in further reducing the NO_x levels, especially with a view to the use of LFP as an alternative energy source.

Fig. 9 shows the chromatogram for the total ions obtained from the BTEX analysis of the samples collected during the tests, where the peaks corresponding to benzene, toluene, ethyl-benzene, m-xylene/p-xylene and o-xylene, and can be observed, with retention times of 2.285; 3.497; 5.972; 6.231 and 7.048 min,

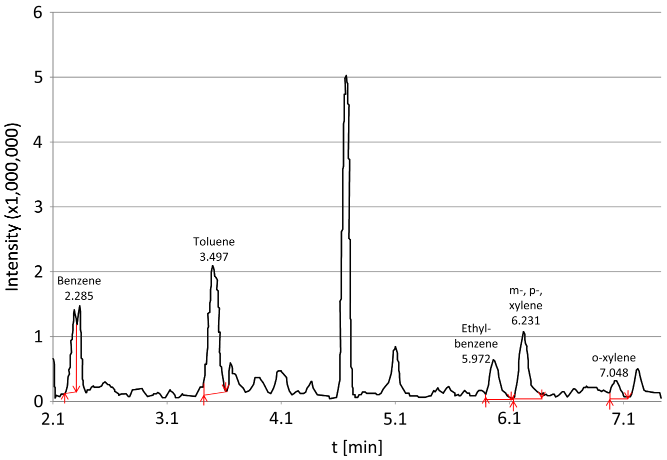

Fig. 9. Chromatogram of total ions obtained in the BTEX analysis.

respectively. TOC concentrations remained below the limits of the regulations considered.

4. Conclusions

Increasing the use of wastes with a high calorific value from the meat processing industry as substitute fuels in industrial combustion processes is an effective option to reduce energy costs and the environmental problems associated with waste disposal.

The information obtained from the biomass characterization was important for the setting of the operational parameters in the combustion tests performed and the TGA/DTG data allowed a better understanding of initial and final biomass degradation temperatures. The combustion behavior observed through thermogravimetric analysis was reproduced during the tests in the horizontal cyclone type combustor.

Besides the higher ash content in comparison with SD, the lower heating values of LFP and LFG were 36.55% and 40.12% higher, respectively, indicating their high potential for use as fuels.

A greater degree of slagging and fouling was predicted through the ash fusibility correlations for LFP combustion compared to SD and LFG, due to its characteristic ash composition, also confirmed by the low fusibility temperatures determined for LFP derived ash. The use of ferric sulfate ($Fe_2(SO_4)_3$) in the physicochemical wastewater treatment that originates LFP modifies the base-to-acid $B/A_{(+P)}$ ratio by increasing the Fe_2O_3 concentration in the ash which favors the occurrence of agglomeration. In the combustion system studied, even working with a short residence time inside the combustion chamber due to the high velocity promoted by the cyclone formed, the occurrence of such problems was observed.

As no data on the combustion of meat processing or slaughterhouse wastes are currently available for comparison purposes, but the pollutant emissions reported in this paper were compared with emission limits established by the Brazilian, the American and the German guidelines for the combustion and co-combustion of wastes.

The emissions of CO, CO_2, C_xH_y and TOC were well controlled during the tests performed and their concentration remained below the regulation limits considered for both biomasses, except CO in the SD combustion test in relation to the German guidelines, which refer to waste incineration and are stricter than the other regulations.

The effect of the biomass composition on gaseous emissions was clearly observed, especially considering the N and S fuel contents in LFP, which led to concentrations of these pollutants being higher than the established limits.

The use of organic solid waste originating from the meat processing industry investigated in this study as a fuel in the cyclonic combustor studied is feasible, however, further research is required concerning the control of SO_2 and NO_x emissions to avoid exceeding the very strict emission limits as well as the occurrence of fouling and slagging.

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